# APPENDIX B

# STEERING, PEDAL, AND MANUAL ACTIVITY IN DRIVER WORKLOAD ASSESSMENT

# APPENDIX B. STEERING, PEDAL, AND MANUAL ACTIVITY IN DRIVER WORKLOAD ASSESSMENT

## MOTIVATION

The driver relies heavily on visual information to safely control the vehicle. This control is accomplished by manipulation of vehicle controls, i.e., the steering wheel, the accelerator, the brake, and (less often) the transmission. It is plausible to hypothesize that in-vehicle device use can disrupt the driver's control activities. This hypothesis implies that measures of steering, accelerator, and brake activities are candidate driver workload measures. Furthermore, such measures are safety-relevant to the extent that driver control inputs, mediated through the dynamics of the vehicle and driving condition factors, affect driver-vehicle performance measures of lane keeping, speed maintenance, and car following.

Steering behavior has been used to assess primary driving task difficulty and the impact of including a secondary task (e.g., an in-cab device task), as well as the effects of fatigue. For example, Safford and Rockwell (1967) found that over a 24-hr period steering reversal rates increased relative to the first hours of driving. Wiener, Curry, and Faustina (1984) similarly reported that lack of sleep led to a statistically significant increase in steering reversals in a simulated driving task. The interpretation attached to such effects is that fatigue leads to poorer or more erratic steering performance. Drory (1985) conducted a simulator study of fatigue in truck drivers and found that, compared to just driving, steering wheel reversal rates decreased with the addition of secondary tasks; this was taken as indicating the beneficial effects of in-cab tasks to offset driving fatigue effects. Studies such as these suggest that steering performance measures may be indicative of driver drowsiness and recent drowsy driver detection research has made extensive use of steering measures as indicators of driver fatigue (Wierwille, Wreggitt, and Mitchell, 1992; Wierwille, 1994). Specific predictions are that drowsiness involves periods where there is a lack of steering activity followed by abrupt, large steering corrections. It is this 'drift and jerk' steering strategy that is said to be one characteristic of drowsy drivers. As will be seen below, inattention to the driving task is also said to be indicated by periods with little or no steering activity followed by large steering corrections.

McLean and Hoffman (1975) proposed that steering wheel reversals may serve as a sensitive measure of primary driving task difficulty. They reported that steering reversals (defined as the number of times the direction of steering wheel movement is reversed through a finite angle or "gap") increased as sight distance was decreased and lane width was decreased, manipulations that effectively increase driving task difficulty. In a test track study by MacDonald and Hoffmann (as cited in MacDonald and Hoffmann, 1980), it was later found that steering wheel reversal rate increased with narrowing of lanes but decreased when drivers also had to perform a secondary task. However, a subsequent on-the-road study by MacDonald and Hoffmann (as cited in MacDonald and Hoffmann, 1980), was conducted on suburban roads and revealed that steering reversals increased with the presence of a secondary task and were lowest on the roadway segments with the most events (where events included other traffic). MacDonald and Hoffmann (1980) later elaborated on the relationship between steering wheel reversals, driving task demand, and other demands. Seemingly contradictory results might be explained by the following assumptions:

- When driving plus in-cab task demands are within the driver's capacity to cope, the driver copes with an additional task by increasing effort and this effort is reflected in higher steering reversal rates;

- When driving plus in-cab task demands match or exceed the driver's capacity to cope, the driver manages attention in such a way that less attention is available for the steering task and this is reflected in a decrease of steering reversal rates.

A test of in-vehicle attentional demand has been made using these assumptions by Dingus, Antin, Hulse, and Wierwille (1989). They found that the steering velocity measure that showed the greatest sensitivity to in-vehicle task differences was the variance of time the steering velocity measure was zero. The logic was given as follows. Normal alert driving is characterized by use of small, relatively uniform steering corrections to maintain proper lane position. As attentional demand increases past a point where attention is drawn away from the driving task, these small corrections cease and the steering wheel is held constant for some period of time (MacDonald and Hoffmann, 1980). Thus, normal small corrections would be followed by holds in steering, causing variance of the times that the steering velocity is zero during a task to increase. Indeed, the most demanding in-vehicle tasks (as measured by task completion time, visual demand, and other indicators) were those with the greatest variance in the time the steering velocity was zero. Similar results were found when the percent of task time that the steering velocity was zero was used as a response measure (Dingus, Antin, Hulse, and Wierwille, 1986). Antin, Dingus, Hulse, and Wierwille (1990) reported (without presenting numerical results) that a measure, percent steering-zero, was sensitive to alternative route guidance aids and that an electronic moving-map route guidance system induced more steering holds than a paper map. Thus, steering measures have proven to be useful in driver workload assessment as well as driver fatigue studies.

More recently, Verwey (1991) reported on the use of a variable called Steering Wheel Action Rate (SAR) to assess workload imposed by a secondary task in an on-the-road study with an instrumented vehicle. SAR was the number of steering actions per second. It was found to increase with the introduction of either auditory or visual secondary tasks in inexperienced drivers. It only increased with visual secondary tasks performed by experienced drivers. According to the earlier assumptions of MacDonald and Hoffman (1980), such secondary tasks must have been within the capacities of the drivers in the context of the primary driving task.

Burnett and Joyner (1993) evaluated the distraction potential of a map-based route guidance system, route instructions, and written notes/maps. The authors report (without presentation of numerical results) that steering wheel variability was greater for the route-guidance system than the other two (baseline) conditions, but only for a certain portion of the experimental route. No differences were found upon approach to a critical exit, though this might be accounted for by factors such as the acquisition of information on the need to exit prior to reaching the exit itself.

Most recently, Dingus and his colleagues have used steering measures in the assessment of the TravTek advanced traveler information system, the largest field study to date on an Intelligent Transportation System (ITS). Dingus, Hulse, Fleischman, McGehee, and Manakkal (in press) examined the effects of age and navigation technique on various aspects of driving by means of assessing the number of large steering reversals (i.e, reversals that exceed 6 degrees). Recall that as workload or attentional demand increases with an in-vehicle task, the frequency of steering corrections tends to decrease. Since the small centering corrections (e.g., 2 degrees to 6 degrees of steering angle) decrease the vehicle tends to drift farther from the lane center and a larger steering input is required to correct the vehicle position error. Thus, large steering inputs (e.g., greater than 6 degrees) increase. Results indicated that the drivers 65 years and older had significantly more large steering reversals per unit time than either drivers 16 to 18 years of age or drivers 35 to 45 years of age. This might be taken to indicate that older drivers were less able to manage additional information processing demands relative to the younger drivers despite more cautious driving behavior, as indicated by other driving measures (e.g., lower travel speed overall).

Dingus, Mollenauer, Hulse, McGehee, and Fleischman (in press) assessed the effects of experience and navigation configuration on driver performance. Results here indicated a decrease in the number of large steering reversals per unit time between local user's first drive and second drive across all navigation configurations (e.g., turn-by-turn iconic visual display with voice call out, turn-by-turn iconic visual display only, electronic map with voice call out, electronic map without voice, written directions, or paper map). This was taken as an indication that with experience, drivers were able to keep their eyes on the roadway a greater proportion of the time and so had to make fewer large corrections in steering.

As these selected studies illustrate, steering measures can be sensitive measures of driver workload. However, steering activity is distinct from driving performance as measured by measures of vehicle heading angle or lane position (MacDonald and Hoffmann, 1980). Heading angle at a given time is roughly the integral of steering position over time and lane position (on a straight roadway, at least) is roughly the time integral of heading angle over time. Thus, vehicle position in the lane is two time integrations away from a steering input. However, steering input is a worthwhile data channel to capture because it may be more sensitive than lanekeeping measures.

On the other hand, steering activity is influenced by many sources simultaneously and therefore may be difficult to interpret. Typical influences in addition to workload are road conditions (e.g., bumpy versus smooth), driver style (e.g., relaxed versus tense), and lack of constraints (there are many steering strategies that allow the vehicle to assume acceptable trajectories). Consequently, researchers or evaluators should be cautious in drawing conclusions about the relationship between workload and steering activity. Correlations may exist but their values may be small.

In addition to steering inputs, accelerator inputs may be assessed. Like steering inputs, driver workload assessment by analysis of throttle inputs is oriented toward indications of intermittent open-loop driving. When a driver's attention is drawn away from the driving task, there is a tendency to maintain the foot in the same position (Dingus, Hulse, Fleischman, McGehee, and Manakkal, in press). Alternatively, the driver may release the accelerator pedal altogether as a preliminary attempt to slow the vehicle down (Dingus, personal communication, April, 1995). When the driver realizes that he or she is going (generally) too slow, the accelerator is depressed to a greater degree than is usual for a normal or continuous adjustment. Thus, accelerator pedal holds, mean hold duration, and variance or standard deviation of accelerator pedal position, as well as number of accelerator pedal releases and total (or percentage) pedal release time appear to be promising indicators of workload . Dingus, Antin, Hulse, and Wierwille (1989) found that accelerator measures were not sensitive to variations in in-vehicle tasks executed while driving in an instrumented vehicle. Antin, Dingus, Hulse, and Wierwille (1990) also reported that there were no differences in accelerator measures (or brake usage) across moving-map electronic displays, paper map, or memorized route conditions. Verwey (1991) found that frequency of depressing the accelerator (as well as brake and clutch pedals) was not affected by executing secondary tasks. Such reports are common in the small body of literature that reports on attempts to use accelerator pedal activation. On the other hand, Dingus (1995, personal communication) has recently completed a study of collision warning systems and reports that warning onset reliably prompts accelerator releases, one indication of driver attention to the warning. Despite the apparent reasonableness of pedal measures, it should be noted that less is known about throttle inputs than about steering inputs for driver workload assessment.

The attentional connection to brake actuations is most evident in brake reaction time. If the driver is attending to an in-vehicle device, this may increase the reaction time to activate the brakes. The number of brake activations might be expected to increase under conditions of high attentional demand if the driver realizes this fact and adopts the strategy of riding the brakes more than usual to support a quick response to an unexpected situations (Dingus, Antin, Hulse, and Wierwille, 1986). By similar logic, the average dwell time per brake application might increase as well. Monty (1984) reported that the number of brake activations and dwell time per brake application were sensitive to the attentional demand of various in-vehicle tasks while driving. On the other hand, Dingus, Antin, Hulse, and Wierwille (1989) did not find brake pedal measures sensitive to differences in road types, or specific tasks asked of drivers while on the road. Verwey (1991) also failed to find brake pedal use sensitive to various secondary task conditions. On the other hand, reaction time measures, especially in simulator studies, have been used to attempt to discriminate among the workload of various experimental conditions. Noy (1990) used brake reaction time in a simulator study and found no statistically reliable relationship between brake reaction time and gaze direction (looking inside or outside during the onset of the deceleration). Noy speculates that this lack of an effect might have been due to the small number of braking events in the simulator. Since on-the-road studies cannot safely include staged events that prompt braking, simulator studies may be the most appropriate means to collect such data in a systematic fashion.

A caveat similar to that presented for steering measures is in order for pedal activity. Pedal actuations are a function of many aspects of vehicle control and should therefore be interpreted with caution in regard to workload influences.

## INSTRUMENTATION NEEDS

The instrumentation needed for capture of driver control inputs and manual activity are discussed below.

### SENSOR SUITE

Steering Sensors. There are several options for the collection of steering data. These include steering position string potentiometers wrapped around the steering shaft, steering pitman arm position stringpot or DCDT (DC differential transformer) or linear potentiometer, and turn sensor assemblies (rotary encoders) that attach to the steering column and measure angles by various means. Given a clean steering wheel position channel, steering velocity can be determined by means of numerical methods, e.g., 5-point numerical differentiation. It is usually better to obtain steering velocity from a velocity (rate) sensor on the steering column. This device is simply a tach generator whose output is proportional to rotational velocity. It should also be noted that pitman arm sensors pick up a substantial amount of road disturbance and so must be filtered judiciously to eliminate such noise.

Accelerator Sensors. A linear potentiometer attached to the accelerator can be used to measure the percent of pedal throw (0% for pedal release to 100% for throttle in full open position). Given a clean accelerator pedal channel, accelerator pedal rate can be determined by numerical differentiation of the position signal. There are also devices available that are capable of providing output proportional to linear velocity of movement.

Brake Pedal Sensors. The simplest sensor is a simple ON/OFF switch (e.g., the signal to the brake lights would work). In addition, a pressure transducer would be useful to measure the percent (or actual pounds per square inch) of force applied in a given braking maneuver.

Manual Activity Sensors. The assessment of the manual resources needed (and available) for in-vehicle device use is a potentially important part of driver workload assessment. Manual activity can be assessed through video cameras, pressure transducers, or capacitive sensitive switches. If a video tape approach is used, the same instrumentation is required as that listed in the Appendix of Visual Allocation Measures in Driver Workload Assessment (Appendix A).

Data Sampling, Range, and Resolution. A sample rate of 30 samples per second is ample for driver workload assessment. The measurement range should be ± 500 degrees with 1.0 degree accuracy for steering position. The measurement range should be ± 6 inches with accuracy to within 0.1 inch if pitman arm DCDT sensors are used. For Accelerator position with either DCDT (DC differential transformer) or linear potentiometer, sensor range should cover a pedal throw of 0-6 inches with resolution of 0.05 inches. Brake activation by means of brake switch or brake light power should handle a voltage input of 0-15 V DC and provide on/off status. On the other hand, measurement brake pressure by means of a pressure transducer should have a range of 0-1000 psi and a resolution of 5.0 psi. If manual activity is captured by means of video tape of the vehicle interior, this should be run at the highest resolution practicable, with a frame rate compatible with NTSC (30 frames per second) or PAL standards (25 frames per second).

## DATA CAPTURE AND CONTROL

The efficient capture of sensor data for driver behavior measures (as well as driver-vehicle performance measures) is best managed by means of a computer on-board the instrumented vehicle. Two possible options for data capture and control of sensor data are Pulse Code Modulated (PCM) data recorders or Data Acquisition computers with analog-to-digital (A/D) converters. The PCM option provides the highest bandwidth, highest data storage density, and easiest means for data transport. The data acquisition computer has the advantage of converting all data to digital at the time of data collection. With this option, a set of anti-aliasing filters must be incorporated to ensure that digitized data have high fidelity. Additionally, an external storage device is essential, especially if a data collection run is to last for any appreciable length of time. Examples of mass data storage devices include high density disk drives and magnetic tape cartridges. It must be noted also that there is more limited bandwidth associated with an affordable direct-to-digital system. Table B-1 presents the advantages and disadvantages of the two options (Battelle, 1994). As with other parts of the data capture system, power must be available, conditioned to avoid data loss or error. A time-code generator is needed as the basic common reference point for all data channels.

## DATA REDUCTION AND FILTERING

The analysis of steering and pedal inputs depends first on appropriate filtering and data reduction. In order to examine the data, software that allows for the simultaneous examination of multiple data streams is helpful, including an examination of a video tape. One type of system that can facilitate this type of data analysis is the Intelligent Transportation System Test Performance Assessment and Evaluation System (ITS TEST PAES) software prepared under government contract by Calspan (for general information see Gawron, 1994).

Table B-1. Comparison of Data Capture and Control Options.

| Consideration | Option A - Record data on PCM data recorder | | Option B - Record data directly to a data acquisition computer | |
|---|---|---|---|---|
| | Advantages | Disadvantages | Advantages | Disadvantages |
| Packaging | Integrated, modular, ruggedized system | Larger than most computers | Small size | Not a rugged as tape, disk drives subject to vibration |
| Power consumption | Moderate power consumption (up to 225 W), runs directly on 12 VDC | | Low power, 50-100 W typical | May need power converter |
| User Interface | Well designed integrated interface with user help | | User may build operating interface | Custom interface to be designed or implemented |
| Software | Debugged firmware | | Flexibility limited only by programming | Software must be purchased and integrated with A/D hardware |
| Data storage | Data storage limited only by willingness to change tapes, up to 4 hr per tape | | | Data limited by hard disk size and archive transfer time |
| Data Bandwidth | Minimum of 88hz sample rate, built in anti-aliasing | | Flexible data rate | Sample rate limited by data storage, separate anti-aliasing filters needed |
| Dynamic range | 96 db dynamic range, (16 bit), 90 db S/N typical, inputs protected to 50 V | | | 60-70 db typical, (10-12 bits) 50 db S/N typical inputs protected to 20 V |
| Cost | Low integration and operating cost | High hardware cost | Low hardware cost | High integration and operational cost |

## FUNDAMENTAL DATA

The following sensed data are required for driver workload measures based on steering inputs.

Steering Position: This is the steering wheel angle as a function of time. Assuming a neutral position (centered steering wheel) set to 0 degrees, then steering wheel positions to the left are in negative degrees while steering wheel positions to the right are in positive degrees. Throughout, the units of measure are (signed) degrees or radians.

High-pass Steering Position: High-pass steering position data is obtained by applying a high-pass digital filter with 0.075 Hz or approximately 0.471 radians/sec corner frequency and roll-off below the corner frequency of 20 dB/decade. The purpose of the high pass filter is to remove slow steering trends due to road curvature.

These sensed data provide the basis for the following fundamental measures:

Steering Hold: A steering hold is defined to occur when the steering wheel velocity falls within the zero dead band range for a duration of 0.4 sec or longer. See Figure B-1 for a graphical depiction of steering holds.

Steering Reversal: A steering reversal is defined to begin when the steering velocity leaves a zero dead band and ends when the steering velocity enters the zero dead band. The starting point of a reversal will be the 1st sample point that falls outside of the zero range, and the end point will be the 1st sample point that falls back into the zero range. See Figure B-2 for a depiction of Steering Reversals. Note that Figure B-2b depicts the magnitude of a steering reversal as well.

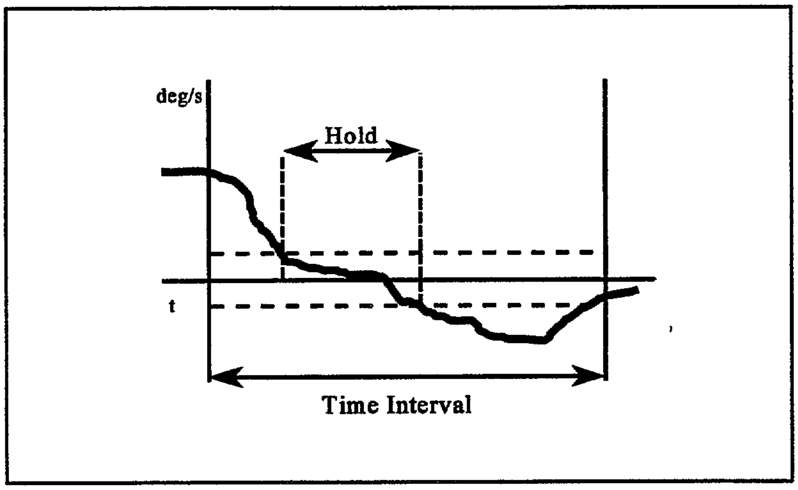


Figure B-1. Occurrence of a Steering Wheel Hold

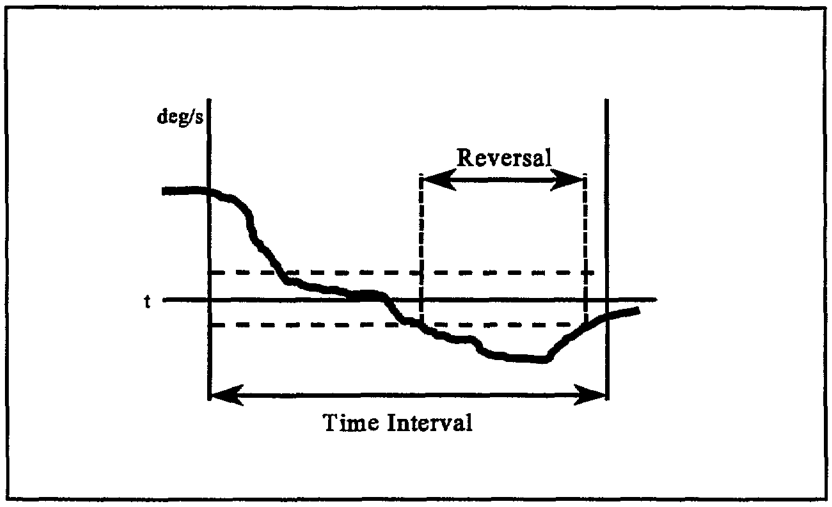


Figure B-2.a  Occurrence of a Steering Wheel Reversal

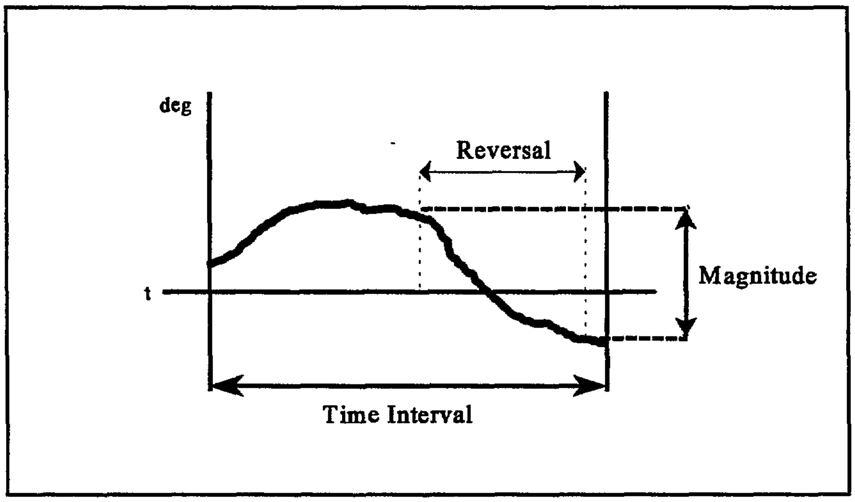


Figure B-2.b. Steering Wheel Reversal's Magnitude

Figure B-2.  Graphical Depictions of Steering Reversals.  See text for explanation.

Steering Zero Crossings

Steering zero crossings are defined as the number of times that the steering position passes from a magnitude of $\zeta$ or greater in one direction, through zero, and then to a magnitude of $\zeta$ or greater in the other direction. More specifically, the procedure for deriving steering zero crossings is

- Run a high pass digital filter (double pass, 0.075Hz, single pole) on the filtered steering wheel position data in order to remove low frequency noise (dc component).
- Determine the HP steering position data zero dead band based on test run data. (Dead band limits are $\pm\zeta$).
- A zero crossing occurs when steering position enters the zero band and exits the band on the other side, resulting in a change of sign in the steering position. See Figure B-3 for a depiction of Steering Zero Crossings.

From these fundamental measures, the steering measures of performance (MOPs) in Table B-2 may be derived. Similar definitions and analyses apply to the accelerator measures and brake measures (see Table B-3). The tables each consist of the following elements:

- Operational definitions of each MOP;
- A workload interpretation, i.e., a prediction of how the MOP should vary with increased workload.

The analysis of MOPs may be conducted using traditional inferential statistical methods. Specific statistical methods that are applicable include t-tests, analysis of variance (ANOVA), and various multivariate procedures (e.g., regression methods, multivariate analysis of variance, cluster analysis). In addition, graphical depictions of univariate and multivariate data are applicable. The references at the end of this appendix provide examples of various analytical procedures.

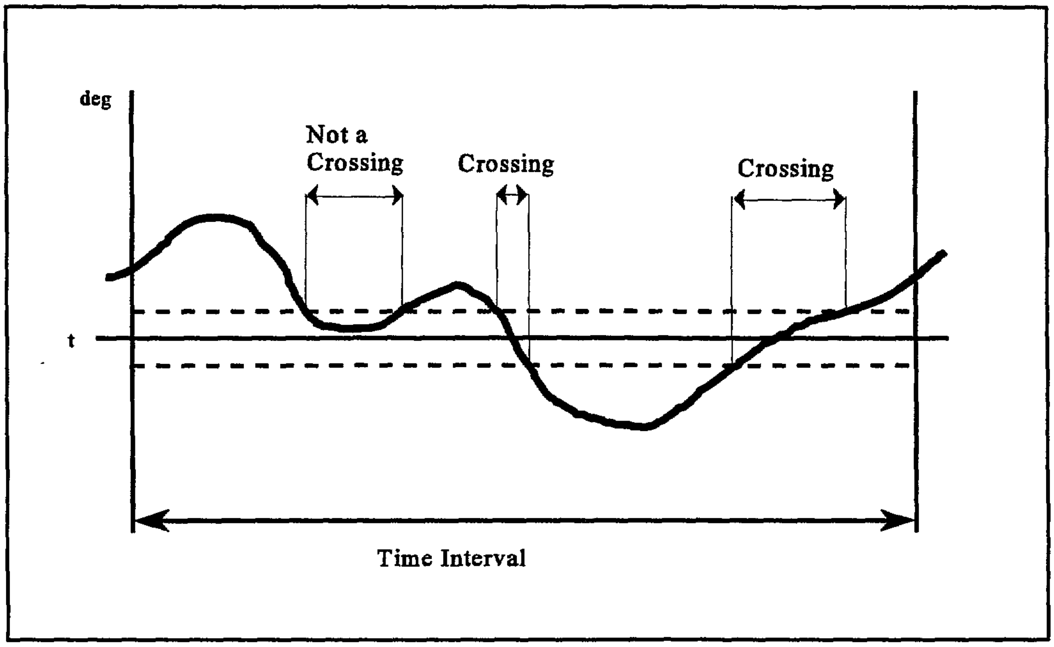


Figure B-3. Graphical Depiction of Number of Zero Crossings. See text for further explanation.

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Table B-2. Steering Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver.

| | |
|---|---|
| **Steering PositionVariance (STPVAR) and Standard Deviation (STPSDEV):** | |
| | These are two measures of the variation in steering wheel position over a sample interval of time.<br>$$STPVAR = \frac{\sum_{i=1}^{n} (\delta(i) - \bar{\delta})^2}{n}$$<br>$$STPSDEV = \sqrt{STPVAR}$$<br>where STPVAR is steering variance in degrees$^2$<br>STPSDEV is steering standard deviation in degrees<br>δ(i) is steering wheel position at sample i<br>δ-bar is mean steering wheel position for the sample interval<br>n is the number of samples in the sample interval |
| Workload Interpretation: | When the driver attends to the lanekeeping task, the driver makes continuous, smaller steering corrections, typically in the range of 2 to 6 degrees for passenger cars. With increased attention to in-cab tasks (or other distractions), the frequency of steering corrections per unit time tends to decrease. Since small steering corrections decrease, the vehicle tends to drift further from the lane center and this requires a larger corrective steering input (generally greater than 6 degrees for a passenger car) subsequently. If small steering corrections decrease and large corrections increase, steering wheel position variance (or standard deviation) should increase with increased workload demand.<br><br>Note: Variance measures may be more sensitive in a statistical sense because of the wider range of values results with the variance calculation. The advantage of the standard deviation measure is that it is in common engineering units, not squared units. |

Table B-2. Steering Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

| | |
|---|---|
| **Number of Steering Holds** = Total number of holds within a sample time interval. | |
| Workload interpretation: | If in-vehicle device demand is high, the driver will have to direct his or her attention to the device, numerous times. During such periods, the driver may hold the wheel relatively still then make a corrective input after taking a glance to the roadway. Thus, the number of steering holds may increase as task demand increases.<br><br>Note that number of steering holds and steering hold duration may trade off within a fixed sample interval. That is, very long hold durations may be indicative of high workload demand yet may be associated with fewer rather than more steering holds. Thus, it is important to consider the two measures together, especially if the sample interval is fixed rather than allowed to reflect task completion time. |

Table B-2. Steering Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

**Mean duration of steering holds**:

$$\textit{Mean Steering Hold} = \frac{\sum_{i=1}^{J} \textit{Steering Hold Duration}_j(i)}{J}$$

The mean steering hold duration is the sum of individual steering hold durations (steering hold $\text{duration}_j$) divided by the number of steering holds in the sample interval, J.

Workload interpretation: Given that steering holds may represent open loop control periods when the driver is attending to a task other than the driving task, longer mean steering holds are associated with higher workload demands.

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Longer holds on average imply greater attentional demand than shorter holds. It is acknowledged that number of steering holds and mean duration of steering holds measure somewhat different processes. Per unit of time, more steering holds imply shorter durations per hold. One interpretation of this is that the in-vehicle task requires multiple glances (and holds) for task completion. On the other hand, long hold durations, like long visual glance durations, imply greater demand as well and also merit assessment.

Note that mean duration of steering holds can only be evaluated if there is at least one hold within the sample interval.

Table B-2. Steering Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

**RMS Steering Velocity Variance (STVRMS) and Steering Velocity Variance (STVELVAR):**

$$STVRMS = \sqrt{\frac{\sum_{i=1}^{n} \dot{\delta}(i)^2}{n}}$$

$$STVELVAR = \frac{\sum_{i=i}^{n} (\dot{\delta}(i) - \dot{\mu})^2}{n}$$

Workload Interpretation: RMS Steering Velocity and Steering Velocity Variance may increase or decrease with increasing in-vehicle device workload (Dingus, 1987). If the driver holds the steering wheel when attentional demand is high instead of performing the normal small corrections, the both measures would decrease with increasing workload. If on the other hand, the vehicle begins to drift off the road, the driver might "jerk" the wheel during high workload situations to correct the vehicle lane keeping error, in which case these measures should increase with increasing workload.

Note that RMS measures are identical to the square root of variance measures only if the mean of the measured variable is zero. It can be demonstrated that variance measures are not affected by a constant offset, a useful property if such a noise source is present in the data stream.

Table B-2. Steering Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

**Steering Velocity Percent Zero Average (STPZAV):**

$$STPZAV = 100 * \frac{\sum_{i=1}^{J} steering\ hold\ duration(i)}{Sample\ interval\ Duration}$$

**Steering Hold Variance (STPHVAR):**

$$STPHVAR = \sum_{i=1}^{J} \frac{(steering\ hold\ duration(i) - mean\ steering\ hold\ duration)^2}{J}$$

Workload Interpretation: STPZAV is basically a measure of the average time that the steering wheel is held during a task (Dingus et al., 1986). This measure might increase with increased attentional demand if, as anticipated, small steering inputs disappear when the driver is distracted from the driving task.

STPHVAR is essentially the variance of the time that the steering wheel is held during a task. If holds are followed by larger steering inputs (to correct relatively larger lane drift), then this response measure should increase with increased attentional demand (i.e., holds followed by jerks to correct lanekeeping error). Note that this value can only be evaluated if there is a least one hold in the sample interval.

Table B-2. Steering Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

| | | |
|---|---|---|
| **Number of steering reversals per unit time**: | | See definition under Fundamental Measures. Generally defined as steering reversals of at least a 2 degree magnitude. |
| **Number of small, medium, and large reversals**: | Small reversals: | Steering reversals $\leq$ 2 degrees |
| | Medium reversals: | 2 degrees <Steering reversals <6 degrees |
| | Large reversals: | Steering reversals $\geq$ 6 degrees |
| Workload Interpretation: | Steering reversals per second may decrease under conditions of high attentional demand away from the driving task.<br><br>In general, the number of small steering reversals might be expected to decrease and the number of medium or large reversals is expected to increase with greater attentional demand away from the driving task. | |
| **Number of zero crossings**. | See definition under Fundamental Measures. | |
| Workload interpretation: | As a measure of steering activity, the number of zero crossings may decrease with increased attentional demand away from the driving task if the driver is holding the steering wheel while engaged in an in-vehicle task. | |
| **Hand-off-Wheel time**: | This is the time that one hand is off the steering wheel and engaged in in-vehicle device use. | |
| Workload Interpretation: | As manual demand of in-cab device use increases, the hand-off-wheel time may increase also. | |

Table B-3. Accelerator and Brake Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver.

**Accelerator Variance (ACLVAR) and**
**Accelerator Standard Deviation (ACLSDEV):**

These are two measures of the variation in accelerator position over a sample interval of time.

$$ACLVAR = \frac{\sum_{i=1}^{n} (accelpos(i) - \overline{accelpos})^2}{n}$$

$$ACLSDEV = \sqrt{ACLVAR}$$

where ACLVAR is accelerator position variance in degrees$^2$
ACLSDEV is accelerator position standard deviation in degrees
accelpos(i) is accelerator position at sample i
accelpos-bar is mean accelerator position for the sample interval
n is the number of samples in the sample interval

Workload Interpretation:

When the driver attends to the speed maintenance task, the driver makes continuous, smaller accelerator corrections. With increased attention to in-cab tasks (or other distractions), the frequency of such corrections per unit time tends to decrease. Since small accelerator corrections decrease, the vehicle tends to slow down and this requires a larger corrective accelerator input subsequently. Since small corrections decrease and large corrections increase, accelerator position variance (or standard deviation) should increase with increased workload demand.

Note: Variance measures may be more sensitive in a statistical sense because of the wider range of values results with the variance calculation. The advantage of the standard deviation measure is that it is in common engineering units, not squared units.

Table B-3. Accelerator and Brake Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

| | |
|---|---|
| **Accelerator Reversals**: | See definition under Fundamental Measures. Accelerator reversals are the number of times the accelerator velocity changes sign. |
| Workload Interpretation: | As with steering reversals, the number of accelerator reversals is expected to decrease under conditions of high attentional demand away from the driving task. |
| **Number of Accelerator Holds**: | An accelerator hold is defined to occur when the steering wheel velocity falls within the zero dead band range for a duration of 0.4 sec or longer. This measure is a count of the number of such holds in the sample interval. |
| Workload interpretation: | If in-vehicle device demand is high, the driver will have to direct his or her attention to the device, numerous times. During such periods, the driver will presumably keep the accelerator pedal relatively still then make a corrective input after taking a glance to the roadway. Thus, the number of accelerator holds should increase as task demand increases.<br><br>Note that number of accelerator holds and accelerator hold duration may trade off within a fixed sample interval. That is, very long hold durations may be indicative of high workload demand yet may be associated with fewer rather than more accelerator holds. Thus, it is important to consider the two measures together, especially if the sample interval is fixed rather than allowed to reflect task completion time. |

Table B-3. Accelerator and Brake Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

**Mean Accelerator Hold Duration**:

$$Mean\ Accelerator\ Hold = \frac{\sum_{i=1}^{J} accelerator\ hold\ duration(i)}{J}$$

The mean accelerator hold duration is the sum of individual accelerator hold durations (accelerator hold $duration_j$) divided by the number of such holds in the sample interval, J.

Workload interpretation: Given that accelerator holds may represent open loop control periods when the driver is attending to a task other than the driving task, longer mean accelerator holds are associated with higher workload demands.

Note that number of accelerator holds and accelerator hold duration may trade off within a fixed sample interval. That is, very long hold durations may be indicative of high workload demand yet may be associated with fewer rather than more accelerator holds. Thus, it is important to consider the two measures together, especially if the sample interval is fixed rather than allowed to reflect task completion time. It should be mentioned that at least one accelerator hold is needed to compute this measure.

Table B-3. Accelerator and Brake Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

| | |
|---|---|
| **Total Accelerator Hold Time** = | $$\sum_{i=1}^{J} Accelerator\ Hold\ Duration(i)$$ i.e., total accelerator hold time is the sum of all accelerator hold durations in the sample interval. |
| **Proportion Accelerator Hold Time**: = [Total Accelerator Hold Time / Sample Interval] | |
| Workload Interpretation: | The total accelerator hold time (or proportion of time) provide other measures of attentional demand. The percentage measure may be used when there is a need to normalize total time measures based on the length of the sample interval. As workload demand increases, total time and proportion of the time the accelerator is held should increase. |
| **Accelerator Releases**: | The number of times that the accelerator is in its null position (e.g., effectively 0% of throw). |
| Workload Interpretation: | Accelerator Releases may be one workload management strategy (besides holds) that allows the driver to "slow" the driving world down somewhat while engaged in an in-vehicle task or other distraction from the driving scene. If this strategy is used, the number of releases should go up with higher attentional demand. |

Table B-3. Accelerator and Brake Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

**Mean Accelerator Release Duration**:

$$\textit{Mean Accelerator Release Duration} = \frac{\sum_{i=1}^{J} \textit{accelerator release duration}(i)}{J}$$

The mean accelerator release duration is the sum of individual accelerator release durations, accelerator release duration(i), divided by the number of releases in the sample interval, J.

Workload Interpretation: Given that accelerator releases may represent open loop control periods when the driver is attending to a task other than the driving task, longer mean accelerator release durations are associated with higher workload demands.

Note that number of accelerator releases and accelerator release duration may trade off within a fixed sample interval. That is, very long hold durations may be indicative of high workload demand yet may be associated with fewer rather than more accelerator releases. Thus, it is important to consider the two measures together, especially if the sample interval is fixed rather than allowed to reflect task completion time.

It should be mentioned that at least one accelerator hold is needed to compute this measure.

**Brake Application (BRNUM)**: The number of times the brake pedal is depressed sufficiently to activate the vehicle brake lights.

Workload Interpretation: It is speculated that when the in-vehicle task becomes difficult, the driver rests a foot on the brake pedal to quickly take action when the driver redirects vision to the forward view. Thus, the number of brake activations may increase with increased attentional demand away from the driving task.

Table B-3. Accelerator and Brake Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

| | |
|---|---|
| **Brake Reaction Time**: | The time interval from the onset of an event (e.g., traffic control signal changes, lead vehicle brakes, pedestrian steps into the driving lane) to application of brakes (see previous definition). |
| Workload Interpretation: | Longer brake reaction times are normally associated with higher attentional demand away from the driving task. |
| **Brake Dwell Time Average (BRTIMEAV)**: | This the mean time the driver spent with a foot on the brake pedal. <br> $BRTIMEAV = \frac{\sum_{i=1}^{J} Dwelltime(i)}{BRNUM}$ |
| where | BRTIMEAV is the brake dwell time average <br> *Dwelltime(i)* is the dwell duration for brake application *i* <br> BRNUM is the total number of brake applications in the sample interval. |
| Workload Interpretation: | The average brake dwell time may increase if the driver rests a foot on the brake pedal in the face of increased attentional demand away from the driving scene in order to quickly react to unexpected events when the driver returns vision to the road scene ahead. |